Application of a Landscape Evolution Model to Gully Management and Reclamation on Military Lands: Fort Carson, CO Case Study

Annual report submitted to the Army Research Office

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1.0 Abstract

Gullies pose a significant hazard to personnel and property on military land, and also reduce the amount of productive terrain. For these reasons it is necessary to undertake preventative measures against further gully development and remedial measures towards established gully systems. These tasks require the understanding of local gully behavior, including what causes their initiation and propagation, and what reclamation measures will be effective. To gain insight into gully behavior, a recently developed simulation model of landscape evolution, CHILD, is employed. The goal of this report is to illustrate the viability of using CHILD to model the evolution of gully systems. A simple case scenario is studied.

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13. ABSTRACT (Maximum 200 words)

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2.0 Background

Gully erosion on military land poses a threat to life and equipment, in addition to the loss of usable training terrain. Remedial works are thus required to transform gullied areas into usable, safe land. On Fort Carson and Pinon Canyon Maneuver Site (PCMS), Colorado, various remedial works have been undertaken to date in an attempt to remedy the extensive gully problem. The methods included banksloping, revegetation, and bank protection. Some areas have also been purposefully retired from training use. The success of the remedial works is varied however. While some remain healed, with a healthy cover of vegetation, others have been re-eroded. Such results have provided some qualitative information on outcomes of remedial techniques, but to thoroughly deal with the issue of gully erosion, more quantitative work is necessary. The aim of this project is to establish a basis for work on remediating gullies by numerical simulation of gully development using a landscape evolution model.

Gullies are erosional features incised into the landscape, generally with a V- or U-shaped cross-section (Graf, 1988). They pose problems not only in the military scenario, but also to agriculture and transport, and have long been the subject of scientific study. Gullies have been studied in diverse regions; Felfoul et al (1998) related lithology of gullies in Central Tunisia to gully shape; Wijdenes et al (1998) investigated the relationship between headcut morphology and erosive processes in southeast Spain; and Derose et al. (1998) used digital elevation models (DEMs) to quantify the extent of gully erosion in a region of New Zealand. Both experimental work into gully headcut erosion (Robinson and Hanson, 1995), and models of gully headcut advance have been undertaken. A common mechanism involved in these models is plunge pool erosion (Stein et al., 1993; De Ploey, 1989), but DEMs have also been used to predict areas susceptible to gully erosion (Prosser and Abernathy, 1996).

The current level of understanding of gully development is still lacking. One method to progress is to simulate gully development with a landscape evolution model, thus providing a testing ground for theories of gully dynamics. Questions this could help answer include: What erosional processes are responsible for particular morphological characteristics? and, What are the limiting factors in gully erosion? Furthermore, the model could be used to test methods for restoring eroded gullies, by simulating subsequent evolution. Applicability of the recently-

developed landscape evolution model, CHILD, to simulate gully erosion under different conditions, will be tested.

3.0 Setting

Fort Carson is located just below the Colorado Front Range near the city of Colorado Springs. Physiography ranges from low-relief piedmont slopes to rugged foothills. The geology consists primarily of gently- to steeply-dipping Mesozoic to early Cenozoic sedimentary rocks. PCMS is situated in the High Plains grassland of southeast Colorado (Los Animas County), north of the Purgatory River. The mean annual rainfall at Colorado Springs is 16.24 inches (National Weather Service). Over a third of this falls during July and August. The mean number of days with thunderstorms is 57.1 days per year. Over half of these days occur during July and August. The 10 highest one-day precipitation records all fall during the months from June to August. In the past, extensive erosion occurred during intense storms, which predominate in the middle of the year.

4.0 Site Observations

A site visit was made to Fort Carson and PCMS from Thursday the 21st to Saturday the 23rd of October, 1999. During the previous weekend, a significant volume of snow fell on PCMS, although the weather had since been dry. The primary goals were to assess the nature of erosion in the two areas, collect preliminary field data for the gullies, and liase with personnel in the Department of Environmental Compliance and Management (DECAM). The group comprised Greg Tucker, Nicole Gasparini, and Daniel Collins, from MIT; Russell Harmon of ARO; and the Fort Carson hosts, Jeff Linn, Bruce Miller, and a third (DECAM); and Dan Sharps (PCMS). The headwaters of the Taylor and Lockwood Arroyos at PCMS were visited on October 21st, followed by visits to erosion features and erosion control works at Fort Carson on October 22nd. On October 23rd, the MIT group returned to Fort Carson to take preliminary measurements of gullies along the east side of Fort Carson. These measurements included gully and upland gradients and channel width and depth.

4.1 Gully Morphology

Gully channels were predominantly U-shaped to rectangular with steep side walls and a head scarp. They were generally sinuous, although some were uncharacteristically straight, having apparently been drainage ditches or roads since abandoned. One gully in west Fort Carson was observed to shallow markedly downstream.

The side walls ranged in slope from a gentle incline to vertical; most were steep. Planform undulations ranged in scale from centimeters to meters. Side wall features included cracks, rills, trickle conduits, seepage faces, and tunnels (Figure 4.1). Seepage faces, observed in fewer than 50% of the sidewalls, were evident by regions of salt deposition. A few gullies had salt-lined rills emerging from their gently-sloped side walls (Figure 4.2). Salt deposits were observed both at the feet of vertical walls (Figure 4.3) and further up their sides. Slump debris was observed at the bottom of walls (Figure 4.5), but so too was its absence; neither situation was noticeably more common. Absence and presence of debris piles was observed in both the same gully system and also on opposite sides of the same channel. In PCMS, one side wall was being undercut by a chute (Figure 4.4).

Headcuts also ranged in slope from gentle to vertical inclines, with the occasional overhang. They also exhibited cracks but were devoid of apparent seepage faces and tunnels. There were no plunge pools in the headcuts, even at the bottom of a 4.5 m drop. Oftentimes the headcuts were amphitheater-like in shape.

Figure 4.1

Tunnel erosion and cracks on a vertical side wall in PCMS.

Figure 4.2

White salt deposits signifying seepage on a small gully's side wall, Fort Carson. This gully is a failed rehabilitation attempt, where the banks were smoothed, sediment check dams put in place, and the sculpted area revegetated.

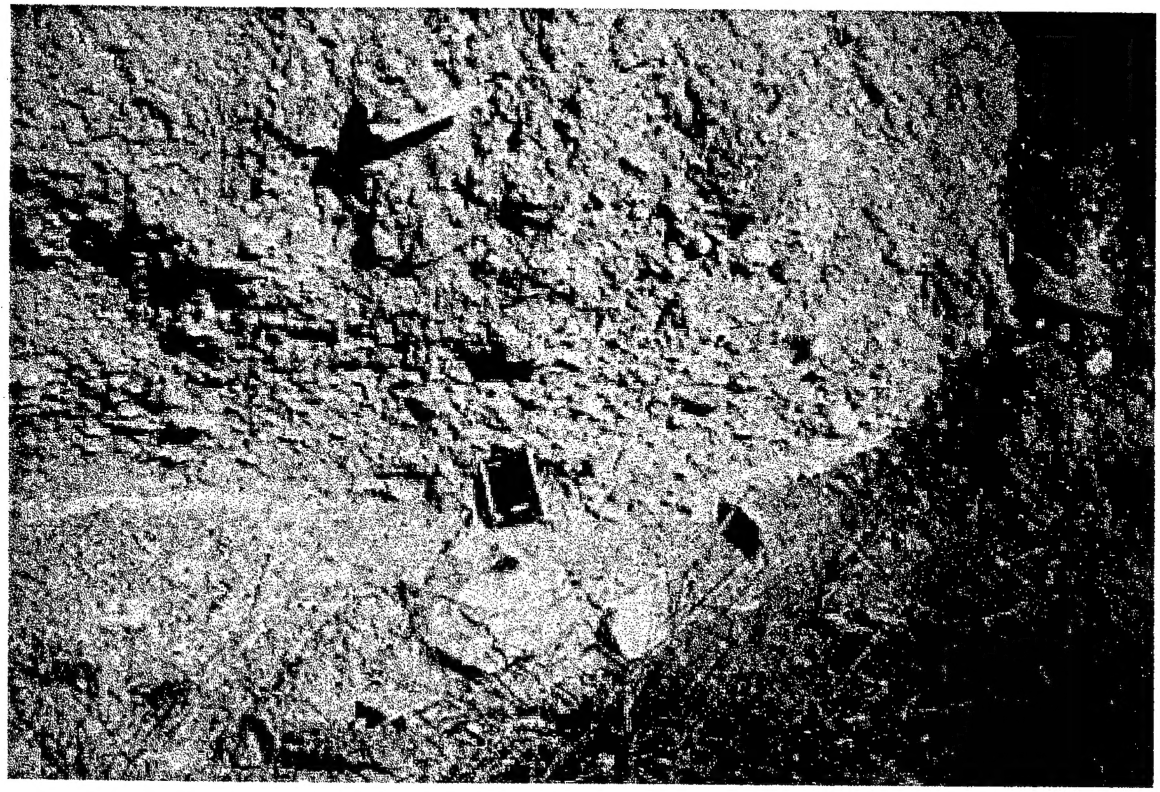

Figure 4.3

Seepage at the foot of a vertical side wall, PCMS. The soil at the foot was slightly damp.

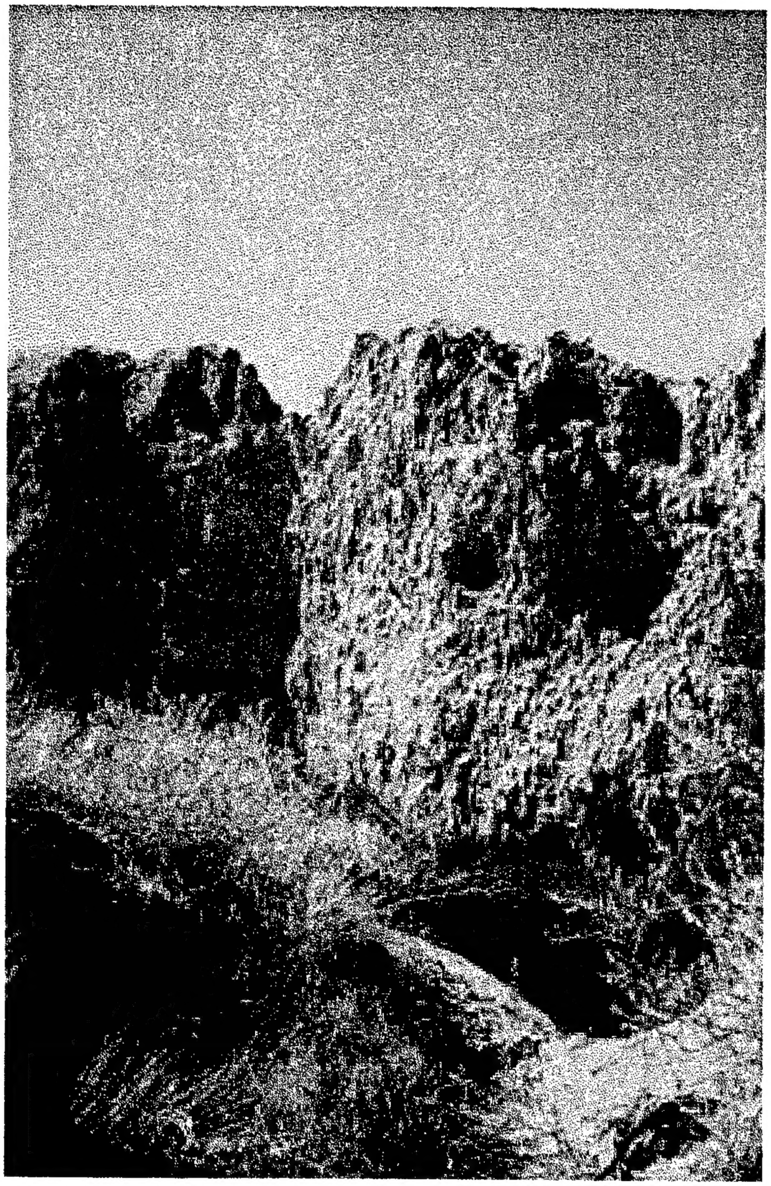

Figure 4.4

Channelized chute undercutting a bank. The side wall is about 2 m high. The channel is being diverted by a large mound. This site was a few meters from the branch's head.

Figure 4.5

Slump debris at the side of a channel, PCMS. The remaining wall is essentially vertical, with a slight overhang induced by the root mat.

4.2 Soils

The soils were generally fine-grained and highly friable, suggesting silt and clay dominance, although a little sand was apparent at PCMS. This implies a low threshold for soil entrainment, when unvegetated. A few gullies had eroded down to bedrock, while the thalweg of another was paved with gravel (Figure 4.6). Some gully floors retained significant moisture content.

4.3 Streams

Most gully streams were ephemeral. Where water was flowing at the time of observation, the clarity suggested negligible sediment transport. In the wider gullies, meandering thalwegs had evolved to create an asymmetric gully profile; the side walls near the outside of the meander were near vertical, while the inside walls were more gently sloped due to the presence of slumped material (Figure 4.6). In a few gully systems, anabranches were present. In one stream, nick-points and plunge pools had developed (Figure 4.7).

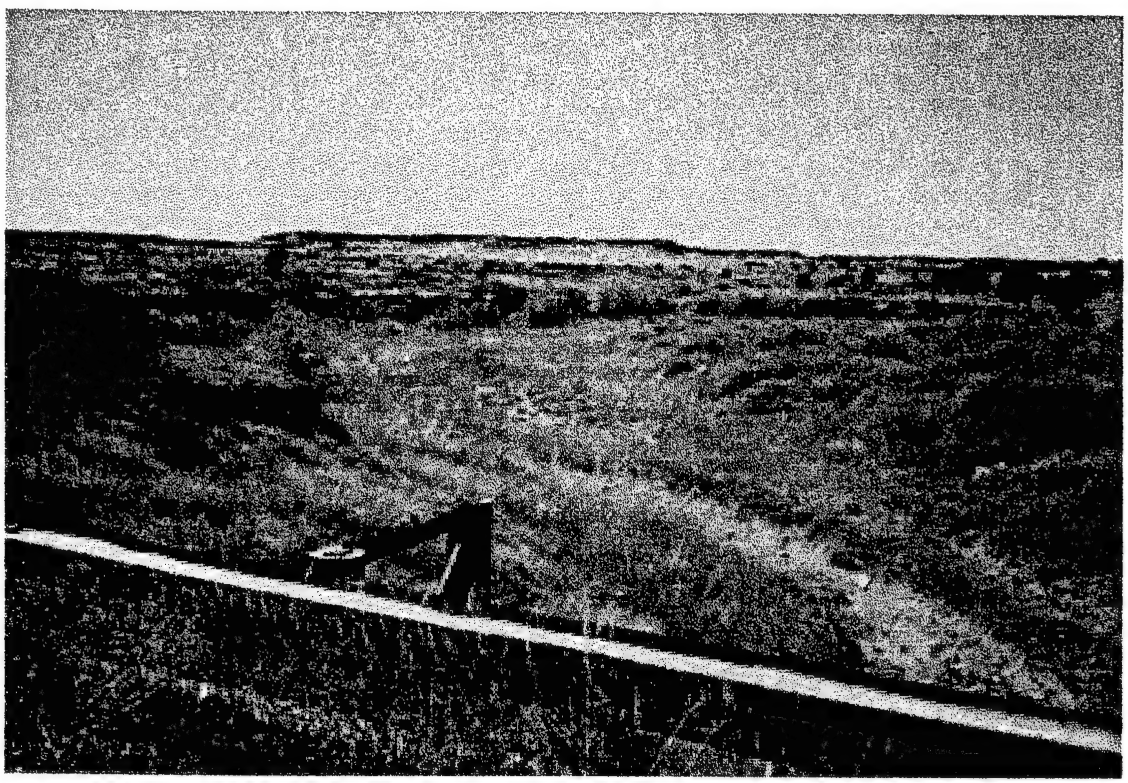

Figure 4.6

Meandering thalweg within a gully, PCMS. On the left are vertical side walls; the right, gentle side slopes. The thalweg is devoid of vegetation, except for a 2 m-high tree. The other regions of the channel bed are covered with grass.

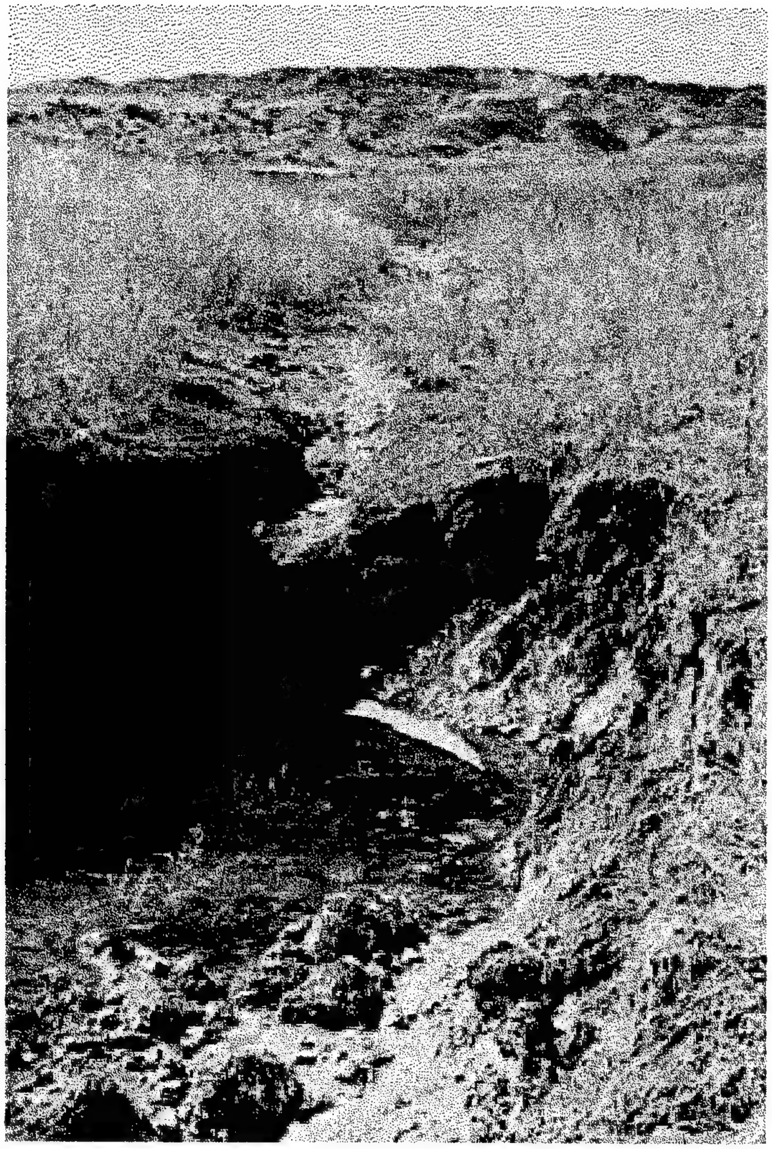

Figure 4.7

Eroded channel with a nick-point and plunge pool. This stream contained a number of such features. The channel was thin, and the water clear. This was the site of failed remedial works (upstream of Figure 4.2), where bank-sloping, check dams, and revegetation had been put in place.

4.4 Vegetation

Vegetation was present in and around the gully floors but generally not on the side walls. The outer vegetation, ranging from grasses to trees, controlled to some extent the position of the gullies. One gully head in the west of Fort Carson was pinned by the roots of a tree (Figure 4.9). Above the tree was a small channel about 0.5 m deep; below the tree the channel abruptly dropped 4.5 m to form a large, rectangular gully of about 4 m width, with a completely flat bed devoid of vegetation. In PCMS, the roots of smaller flora also appeared to provide cohesion to the upper soil horizon, leading to crumbling vertical walls and sometimes overhangs (Figure 4.8). Inside the gullies, vegetation cover ranged from negligible to dense growth. The density appeared to relate to the gully's activity, with active channels having less dense gully-floor vegetation.

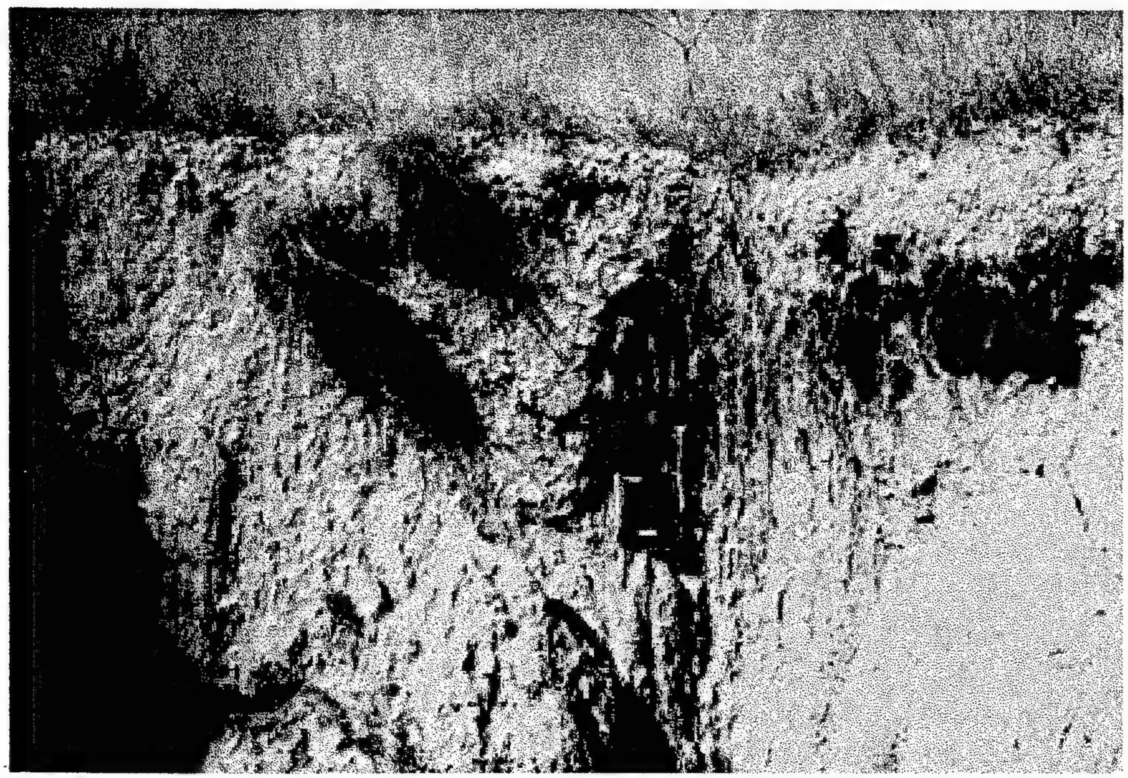

Figure 4.8

Vertical gully head being supported by a root mat, PCMS. Roots can be seen hanging from the bottom of the upper soil layer, which remains intact.

Figure 4.9

Gully head pinned by roots of the tree in the top-left of the image. Just below the tree, the 0.5 m deep, narrow channel drops 4.5 m to a rectangular gully.Tree roots were hanging from the soil below. Inside the gully the soils were damp. Despite the sizable drop, there was no obvious plunge pool at the base.

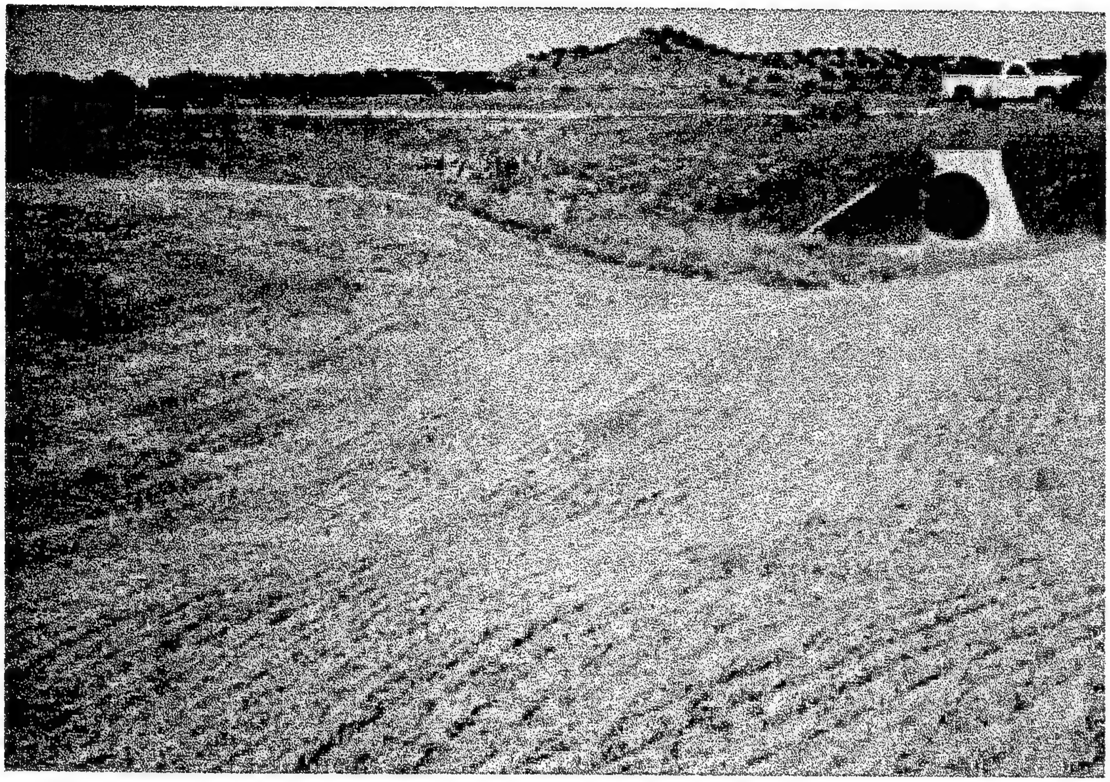

Figure 4.10

Recently-rehabilitated gully with banksloping and mulch cover, PCMS.

4.5 Gully Rehabilitation Work

Of the various rehabilitated gullies viewed at PCMS and Fort Carson, there were both successes and failures. Different modes of restorative methods had been adopted (Figure 4.10); bulldozing side slope material into the channels, raising the channel bottom elevation; bulldozing side material out, thus maintaining the same gully floor elevation; introducing rip-rap to the head and/or side walls; and revegetating headcuts and side walls. The successful gullies were those whose replanted vegetation had time to mature sufficiently, reported as generally three years, before a significant storm event, which would wash away younger vegetation. Gullies whose side walls had been pushed outwards seemed also to be more resilient to subsequent gully erosion. Of the failures, some had undergone extensive erosion during a single storm (Figures 4.2 and 4.7).

4.6 Paleo-Gullies

At the Little Grand Canyon (Figure 4.11), southwest Fort Carson, there was evidence of past gullying and accretion cycles. The stratigraphy visible along the currently-incised gully walls showed an unconformity developed at the bedrock-alluvium contact. At some earlier stage, perhaps in the late Quaternary, incision had occurred, presumably forming gully system of similar form to that present now, after which the gully recovered. This indicates gully erosion and accretion can occur naturally., in this case probably to Quaternary climate changes.

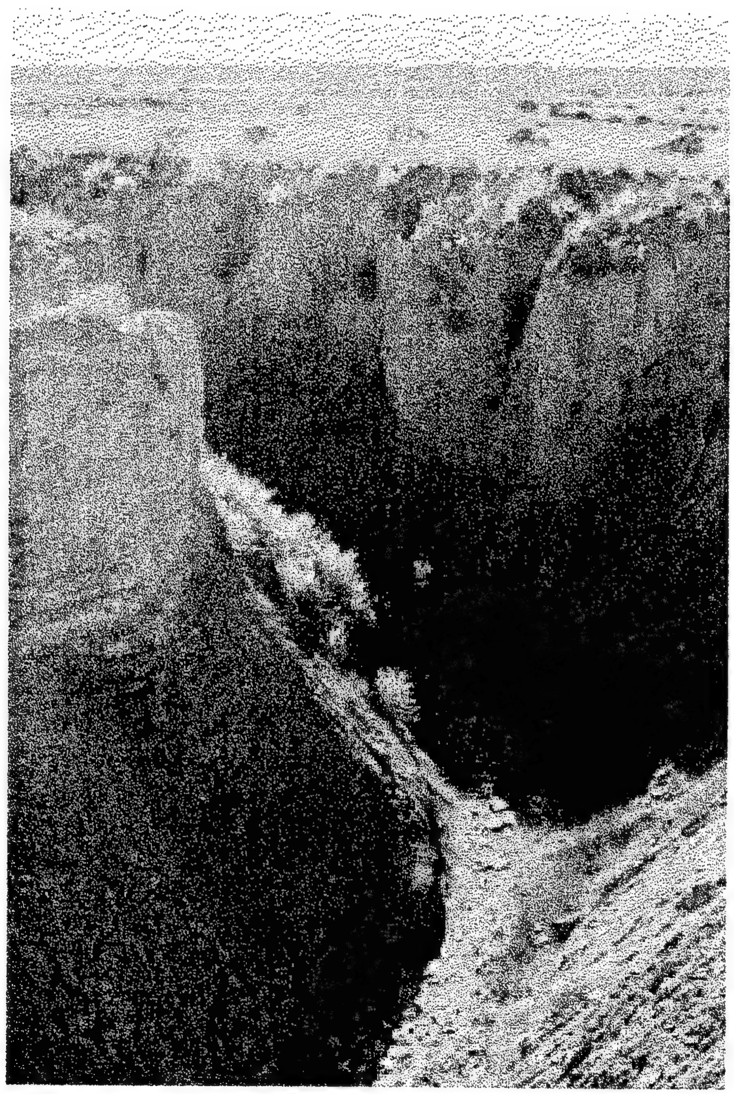

Figure 4.11

The Little Grand Canyon, Fort Carson, displays evidence of past gullying and re-filling events. The 15-20 m high walls are buttressed by slump debris.

5.0 Observations and Inferences on Gully Dynamics

Gully development involves a diverse range of interacting processes. The significance of each depends on the local conditions. As the local conditions vary with space and time, so too does the relative significance of each gullying process. Vegetated land will be less susceptible to gullying than more barren regions; a change in climate to more severe rainfall will predispose an area to gully erosion. Processes also change in the course of the gully's development, as different processes are required to trigger initiation from those which maintain gully propagation.

To construct working hypotheses for gully development in Fort Carson and PCMS, it is first prudent to examine, in general, the processes related to gully formation. Here, the primary causes for erosion are detailed, along with the environmental factors required for these processes to take effect.

5.1 Primary Mechanisms of Soil Movement

The potential processes involved in gully erosion in general are considered to be:

- overland flow;
- mass wasting;
- sapping;
- tunnel erosion;
- plunge pool erosion; and
- channelized flow.

5.1.1 Overland Flow

Overland flow includes both saturation and Hortonian overland flow. Saturation overland flow occurs when the water table rises to the ground surface causing all additional precipitation to go directly to surface runoff. Hortonian overland flow occurs when the precipitation rate exceeds the soil's infiltration capacity. In either case, the flow exerts a shear stress on the soil surface. If the applied stress is greater than the critical stress for particle entrainment, material will be detached and transported. The applied force increases with flow depth, flow rate and local slope, while the

soil's resistive force (the critical shear stress) depends on the properties of the soil and vegetation (Preston and Crozier, 1999). Greater soil cohesion and packing increase the critical shear stress required for movement. Following entrainment, the flow transports the soil downslope. Evidence, indicative of erosion by overland flow, are rills.

5.1.2 Mass Wasting

The dominant gully-related mass wasting processes include slumping and block failure. Slumping is the failure of a slope from reduced support to the soil mass, from either undercutting or a loss of cohesion. Block failure is the detachment of a single block of soil from the wall.

5.1.3 Sapping

Sapping refers to the weakening and erosion of basal support to headcuts and sidewalls by the concentrated groundwater seepage from the ground, leading to the undermining of the banks (Laity and Malin, 1985). Amphitheater-like gully heads are a common expression of sapping-dominated erosion.

5.1.4 Tunnel Erosion

Tunnel erosion is the enlargement of subsurface cavities by water flow (Crouch et al., 1986). The tunnels themselves may evolve from cracks in the soil, burrows, root cavities, or other macropores.

5.1.5 Plunge Pool Erosion

Plunge pool erosion is the detachment of soil particles by the impact of a free-falling jet of water (Stein et al., 1993). For water flow to separate from the ground surface, the flow rate must be sufficiently great at a point of significant increase in gradient, such as a vertical headcut. The plunge pool itself is a localized scour hole which may tend to undermine surrounding slopes.

5.1.6 Channelized Flow

During storm events, gully systems become channels for concentrated flow. This flow is required to remove the eroded material deposited in the channel by bank collapse or other mechanisms out of the active gully area. The removal of the debris adds to the necessary conditions for sustained gully activity. Collapsed banks, for example, would act as supporting buttresses to their adjacent walls, providing resistance against further erosion if not removed. Soil detachment and transport result from the same mechanisms as those for overland flow.

5.2 Secondary Causes of Gully Erosion

All processes require sufficient conditions under which to act. These secondary factors involved in gully erosion pertain to the following:

- climate;
- topography;
- vegetation;
- soils; and
- groundwater.

5.2.1 Climate

Elements of the prevailing climate that affect gully formation and propagation include precipitation intensity and duration. The greater the storm intensity, the more likely Hortonian overland flow will occur; alternatively, the longer the storm duration, the greater the likelihood of saturation overland flow. In either case, increased precipitation will lead to increased runoff and flow velocity. For larger basins, spatial storm extent begins to play a role. Temperature fluctuations about freezing point also play a role, by causing subsurface water to undergo freeze-thaw cycles, thus encouraging crack growth from ice expansion. Cracks may also develop from repeated of wetting and drying.

5.2.2 Topography

Local topography affects gullies in a number of ways. Steeper slopes produce high shear stresses. Converging topography leads to flow accumulation, increasing both flow rate and volume This can result from the microtopography of rills, roads, and drainage ditches to the topography on the hill slope. Local topography is in turn altered by gully propagation, earthworks, or subsidence (by macropore collapse, water table lowering, or seismic settling). The profile of the headcuts and side walls hold significant sway in the type of the erosion - slumping, toppling and plunge pool erosion cannot occur on medium slopes. Gully wall slope also dictates whether vegetation will be able to grow.

5.2.3 Vegetation

Vegetation increases the apparent soil cohesion in the region of the plant roots (Preston and Crozier, 1999), thus increasing the critical shear stress for soil detachment, and also increases infiltration rate (Dunne, 1978) thus reducing runoff. Grazing, fire, drought, vehicle passage, and extended periods of inundation can all lead to vegetation loss, reversing its stabilizing influences.

5.2.4 Stratigraphy and Soils

Soil infiltration capacity affects the amount of precipitation that infiltrates and how much goes to surface runoff. Compaction by animals or vehicles, and infilling of fines by rainsplash or eolian deposition all achieve a reduction in the infiltration capacity. Once water has infiltrated it migrates by advection and dispersion. These in turn depend on porosity, water content, presence of macropores and heterogeneities in soil hydraulic conductivity, such as pans that result in perched water tables. Macropores include freeze-thaw and shrink-swell cracks, animal burrows, and root cavities. They act as flow conduits and may grow by tunnel erosion.

5.2.5 Groundwater

Groundwater conditions have three major effects on gully growth; the influence on saturation overland flow, on seepage, and on soil properties. The higher the watertable, the sooner a state of saturation overland flow will be reached. The greater the rate of groundwater flow, the greater the

role played by seepage and sapping. In addition, saturation of the soil reduces its strength. All factors assist in the erosive process.

5.3 Working Hypotheses for Fort Carson Gully Erosion

An important goal of this project is to establish a set of needs and recommendations for future work. A precursor to gully simulation, knowledge of gully dynamics is crucial, which in turn requires testable hypotheses to be established. Summarized here are the erosion-related processes and conditions most likely to contribute to gullying in Fort Carson and PCMS, which thus constitute the project's hypotheses.

- A necessary condition for gullying to occur is a sufficiently large storm event. Other factors merely predispose the landscape to gully erosion. We are currently in the process of gathering weather data specific to Fort Carson. Through simulation runs, the storm characteristics, duration and intensity, required to initiate and propagate gully erosion may be predicted.
- Vegetation is important in soil cohesion in Fort Carson and PCMS, as evidenced by vertical walls being maintained significantly by plant roots. Its loss is therefore expected to assist in gully development. Destruction of the vegetation armor, through the course of military training exercises, would reduce the cohesive strength of the soil, and decrease the rate and/or depth of infiltration. Both effects are examined with respect to gully initiation. Current questions are: What extent of vegetation cover prevents gully initiation? and, What characteristics of vegetation cover (root depth, percentage cover) halt gully propagation?
- The presence of rills on the margins of the gullies, and on the shallower side walls, provide ample evidence for erosion by overland flow. The semi-arid climate, with short, intense storms, and what we believe are low permeability soils, suggest Hortonian overland flow would predominate. This process is modeled using CHILD. The amount of overland flow required to erode the bare and vegetated soil surfaces in Fort Carson and PCMS will be established through the course of modeling.
- Mass wasting plays a key role in the Fort Carson and PCMS gullies, as evidenced by the debris piles along channel walls. A precursor to bank collapse is soil weakening, arising from sap-

ping, devegetation, or undercutting. The amphitheater-like gully heads suggest a dominant sapping component. The extent of this is yet unknown, nor the precise conditions for the process to occur, however, further research, experimental and numerical studies will lead towards the resolution of the issue.

- The various seepage faces recorded show exfiltraton occurs. This indicates the gully margins become highly saturated during erosive events. Knowledge of the interactions between soil moisture and soil strength, sapping, and vegetation dynamics would be invaluable in the understanding of gully evolution.

While key processes involved in gully erosion in Fort Carson and PCMS have been identified above, it is not precisely known what their relative importance is, nor which are rate-limiting. These issues pose questions to both the initiation and propagation of gully systems.

6.0 Data Compilation

Topographic maps, in the form of DEMs, have been obtained for Fort Carson and PCMS (Linda Moeder, DECAM), in addition to rainfall frequency data from the weather station in Denver. Rainfall data for a station in Fort Carson has been obtained and is currently being processed. A submission has also been made through the Freedom of Information Act requesting additional GIS and meteorological data. This submission is currently awaiting approval from Fort Carson FOIC.

7.0 Preliminary Modeling

Preliminary numerical modeling studies have preformed to investigate the sensitivity of gully initiation to vegetation degradation. The CHILD model, which was developed for USACERL project DACA88-95-C-0017, was used for these experiments. The CHILD model uses an irregular finite-difference gridding method based on the model of Braun and Sambridge (1997) to represent the landscape surface (see Figure 7.1 for a sample topography) (Tucker et al., 1999). Every point, or node, on the landscape has an elevation (z), surface area (a), and a location in space (x,y). In this study the nodes are roughly spaced at 50 meter intervals.

Runoff, which is generated during rain storms, produces fluvial erosion. CHILD uses a stochastic model of rainfall based on the model of Eagleson (1978). Rainfall is modeled as a series of discrete random storm events (Tucker and Bras, 1999). During each storm, the rainfall rate (P) remains constant during the entire storm duration (T_r). Each storm is followed by an interstorm period of duration T_d. Rainfall intensity, duration, and interstorm duration are modeled using an exponential probability distribution given by the following equations:

$$\text{Rainfall intensity, } f(P) = \frac{1}{\overline{P}}\exp\left(-\frac{P}{\overline{P}}\right), \tag{1}$$

$$\text{Storm duration, } f(T_r) = \frac{1}{\overline{T_r}}\exp\left(-\frac{T_r}{\overline{T_r}}\right), \text{ and} \tag{2}$$

$$\text{Interstorm period, } f(T_d) = \frac{1}{\overline{T_d}}\exp\left(-\frac{T_d}{\overline{T_d}}\right). \tag{3}$$

$\overline{P}$, $\overline{T_r}$, and $\overline{T_d}$ represent the mean values of rainfall intensity, duration, and interstorm duration, respectively. Runoff is produced when the rainfall intensity exceeds the infiltration rate (I). The infiltration rate is spatially constant for all of the experiments discussed. Water is assumed to flow from each node on the landscape in the steepest downhill direction. The area drained (A) through any node on the landscape is equal to the sum of the areas of all the nodes upstream of it

($\sum_i a_i$, where i represents each of the upstream nodes, including the node itself). The volumetric runoff rate at any location in the landscape is therefore described as

$$Q = (P - I)A, \tag{4}$$

when $P > I$ and $Q = 0$ otherwise. Runoff is only produced during storm periods.

Running water exerts a shear stress (τ) on the ground beneath it which can produce erosion. Shear is calculated using the following expression:

$$\tau = K_t \bar{P}^{(-3/20)} Q^{9/20} A^{(-3/20)} S^{7/10} \quad , \tag{5}$$

where K_t is a parameter of the soil material and S is the local slope ($S = \frac{\partial z}{\partial \hat{x}}$) (Tucker and Bras, in review). Depending on the conditions of the surface, the ground is often resistant to this shear stress. The ground's resistance to erosion is expressed by its critical shear stress (τ_c) or, in other words, its erosion threshold. Erosion due to running water will only occur when the shear stress surpasses the critical shear stress. The rate of fluvial erosion is expressed as

$$\frac{\partial z}{\partial t} = -K_e(\tau - \tau_c), \tag{6}$$

where K_e is an erodibility parameter and t is time. Equation 6 only holds when $\tau > \tau_c$, otherwise $\frac{\partial z}{\partial t} = 0$. The value of the critical shear stress depends on such factors as the type and condition of vegetation, the texture of the soil and the different materials in the soil. In these experiments, critical shear stress varies only as a function of the state of the vegetation and is spatially constant.

Loss of vegetation has two important consequences which pertain to landscape evolution (Kramer et. al., 1997; Ren and Zhu, 1994). First, a plant's root system increases the porosity of soil allowing more water to infiltrate into the ground. When vegetation is reduced, infiltration rates are also reduced and more runoff is generated, producing higher shear stress values. The

second important aspect of vegetation is that it stabilizes the soil, making it more resistant to fluvial erosion, or, in other words, it increases the critical shear stress. When the strength of the soil is reduced, less runoff is required to create a shear stress greater than the critical shear stress required for erosion. However, without vegetation, not only does the critical shear stress decrease but more water is produced to erode the landscape. The effects of these two factors are investigated using CHILD.

The rainfall statistics used in these experiments are based on a semi-arid climate with intense, short storms. The modeled average annual rainfall is 500mm, average rainfall intensity is 0.6 mm/min, average storm duration is 20min, and average interstorm duration is 13,811min (or about 9.6 days).

Data on infiltration rates was obtained from Zhu et al. (1997). Infiltration rates were measured during sprinkler experiments on different types of land in the Loess Plateau, China. Forested land had the highest infiltration rates of about 0.9mm/min. Barren slopes had a reduced infiltration rate of about 0.3mm/min.

The value of K_e (505 $m^2\ s^2$/kg/yr) is taken from a study of jet scour erosion by Stein et al. (1993). Jet scour erosion or plunge pool erosion is thought to be one of the dominant causes of gully erosion (De Ploey, 1989). The value used for K_t is 0.618 kg $yr^{9/20}/m^{41/20}/s^{49/20}$. This value is calculated as a function of hydraulic geometry and the roughness of the surface. K_e and K_t remained constant for all of the experiments.

The values used for critical shear stress are taken from Prosser and Slade (1994). Their data are from a study on the role of vegetation in gully formation in southeastern Australia. They obtained the critical shear stress for erosion in areas with non-disturbed grass (240 kg/m/s^2) and heavily degraded grass (70 kg/m/s^2).

The first experiment performed was a control case with intact vegetation. The initial condition for this and all of the experiments is a slope of about 5% draining to an opening boundary over which sediment and water can pass over. Sediment and water can only leave the system at the foot of the slope. The critical shear stress value used was that for undisturbed vegetation; the

infiltration rate used was that for undisturbed vegetation. Figure 7.1 shows the change in elevation everywhere on the landscape, or in other words, the amount of erosion, after 500 years of landscape evolution. The high critical shear stress and high infiltration rates do not allow any gullies to form. This illustrates the strength of the landscape to erosion when there is vegetation to hold the soil together. With vegetation in place, no gullies are able to form and the landscape remains stable and usable.

In the next experiment, the sensitivity to increased runoff was examined. The critical shear stress remained at the value for undisturbed vegetation, but the infiltration rate was reduced to the value for a devegetated surface. After 500 years no erosion occurred. There is no figure for this experiment, but a plot of erosion would look exactly the same as Figure 7.1, that is, nothing happens under the same conditions. This experiment illustrates that a change which leads to an increase runoff alone is not enough to produce gully erosion when the strength of the soil remains high. Here the increase in runoff results from a reduction in infiltration, but it is worth noting that a change in climate leading to a comparable increase in rainfall intensity would produce the same result.

Erosion started to take place when critical shear stress was reduced to the value for degraded vegetation. Figure 7.2 shows the plot of erosion after 500 years with critical shear stress at its degraded value and a high, unchanged infiltration rate. One gully has developed. If this same experiment is performed with both the degraded vegetation critical shear stress value and the low infiltration rate representing barren soil, the effects are even worse. After 500 years there are six gullies instead of one (Figure 7.3). When critical shear stress is low, an increase in runoff is of considerable importance.

These numerical experiments highlight the importance of vegetation in erosion prevention. When vegetation is well-established gullies cannot erode into the landscape. The most important effect of vegetation in these experiments is the resistance to erosion which it adds to the soil. Significantly decreasing the erosion threshold is alone enough to produce gullies. However, when the soil has lost is strength due to vegetation degradation, the effects of increased runoff magnify the destruction of the landscape. These results suggest that changes in the critical shear stress of the soil are of primary importance, and that these changes are exacerbated by changes in runoff.

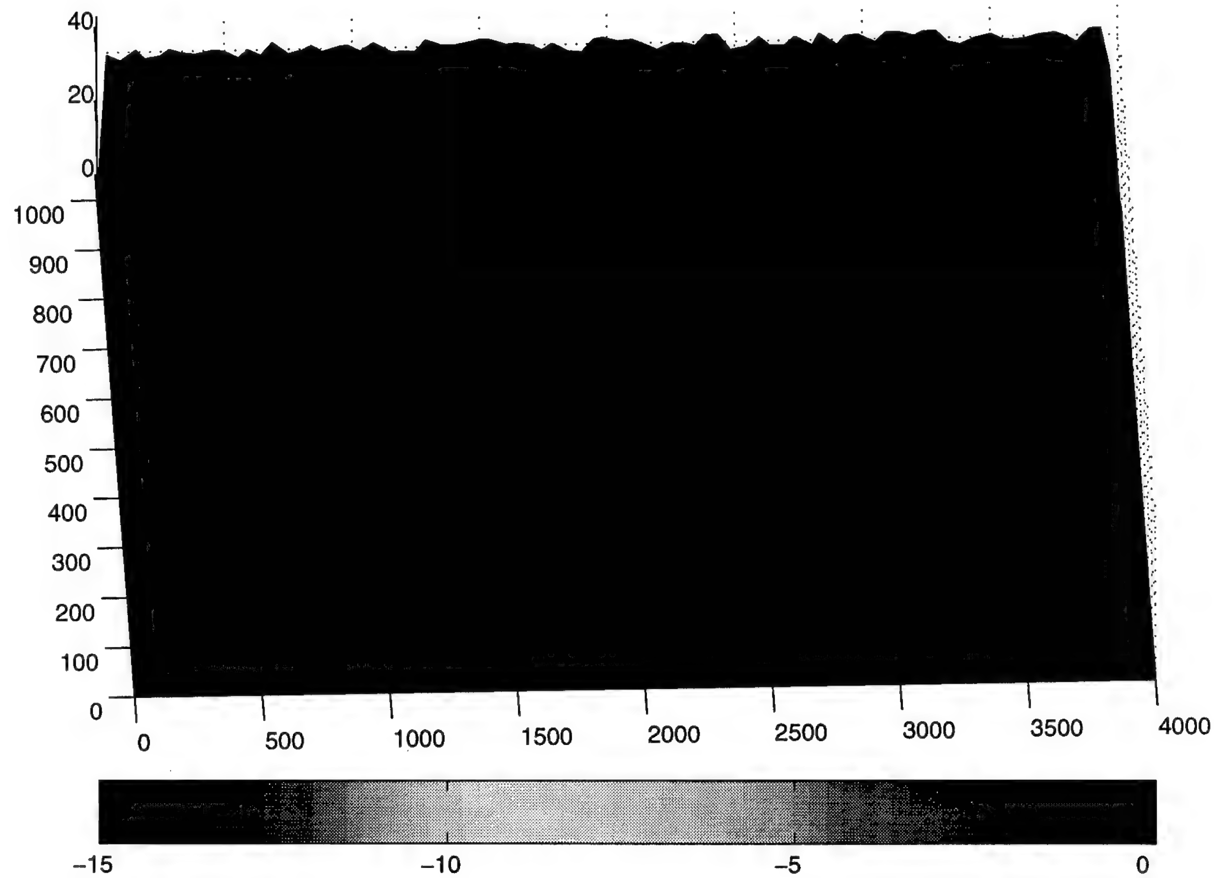

Figure 7.1

Coloring is by elevation change since initial condition of a flat slope.
100,000 years, In tact vegetation, that is high critical shear stress and high infiltration rates.

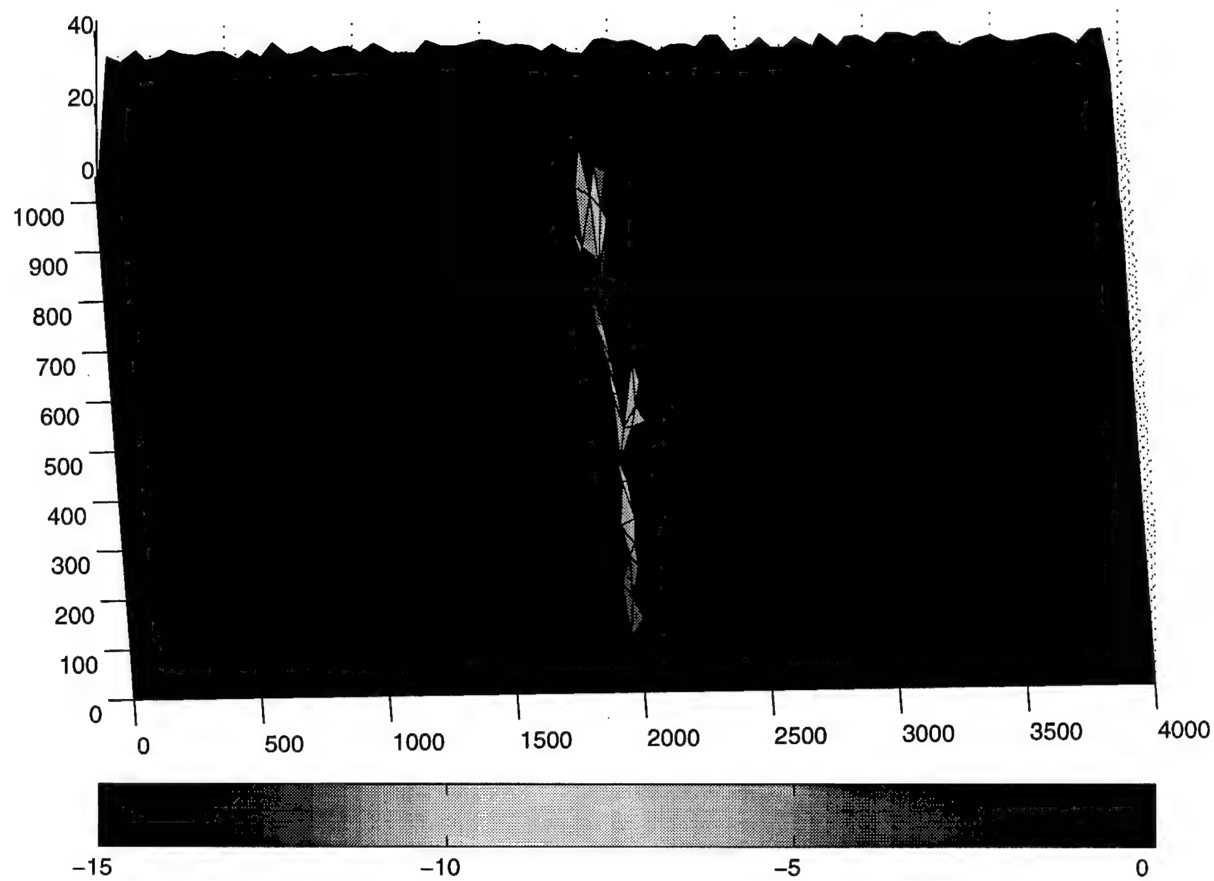

Figure 7.2

500 years of evolution since critical shear stress was decreased to degraded vegetation value, but infiltration rate remained high. Shading is by the amount of erosion since the initial condition (flat slope with no gullies).

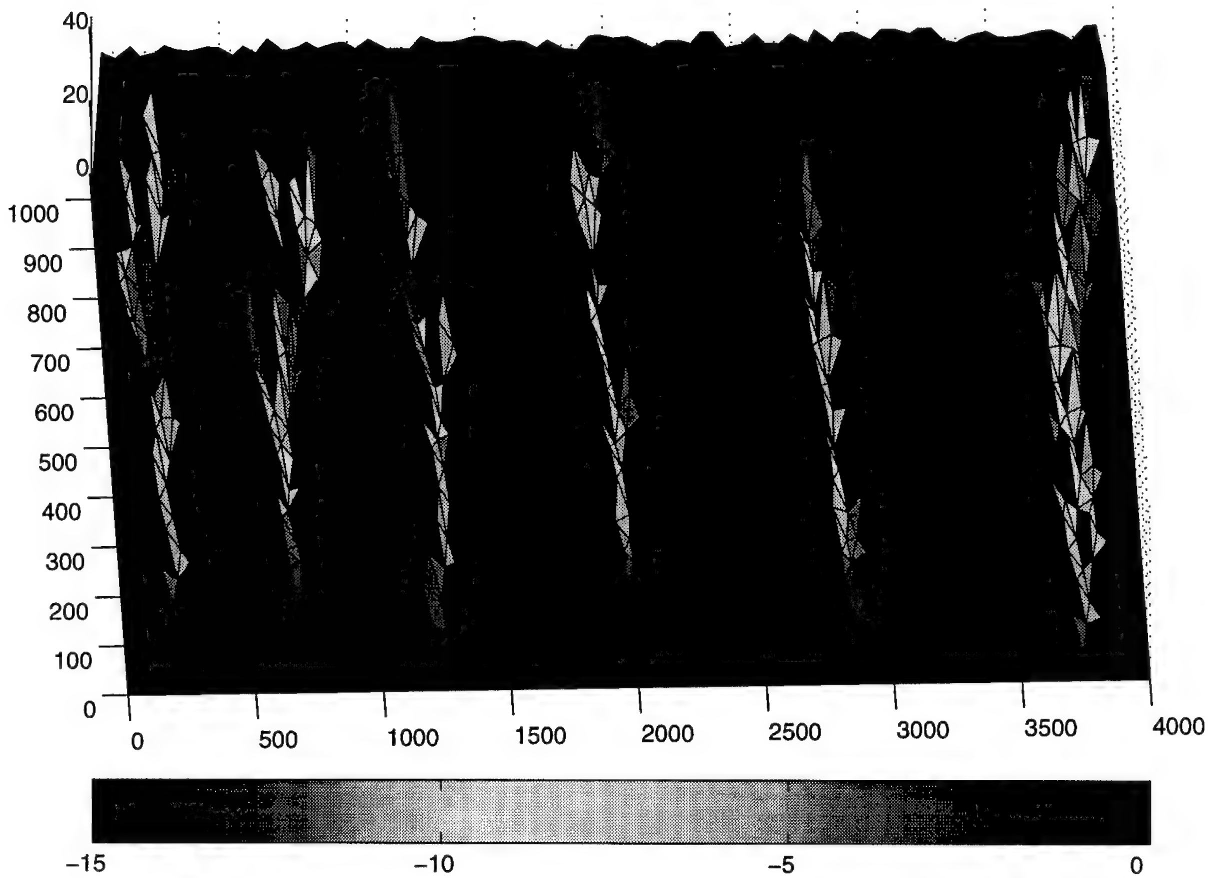

Figure 7.3

500 years of evolution with a low critical shear stress (degraded vegetation value) and a low infiltration rate. Shading is by the amount of erosion since the initial condition (a flat slope with no gullies).

8.0 Conclusions

The processes identified as being potentially key to gully erosion in Fort Carson and PCMS are overland flow, mass wasting, and sapping. Additional efforts are hence required to evaluate the role and relative importance of these factors. The main preconditions for such erosion are intense rainfall events, minimal vegetation, and highly saturated soils.

The preliminary modeling work demonstrates the role runoff volume and soil strength play in gully erosion. High runoff and a low soil strength enhance susceptibility to gully erosion; the effect of their combination is even more pronounced. The model runs further demonstrate that CHILD is capable of simulating gully evolution, albeit over a small range of scenarios. Nevertheless, CHILD has the ability to examine far more complicated scenarios.

Through the course of the report, various questions pertaining to gully evolution in Fort Carson and PCMS have arisen:

- What are the environmental thresholds (vegetation, rainfall, soil properties) involved with initiation of gully erosion?
- What is the relative importance of overland flow, sapping and mass wasting in gully propagation?
- What are the characteristic features produced by these process?
- What are the dominant processes responsible for halting gully erosion?
- What are the environmental thresholds that lead to cessation of gully erosion?

To answer these questions additional data area required. These include:

- local rainfall statistics for each month, in the process of being obtained;
- soil infiltration capacities (expected to come from STATSGO), also in the process of being obtained;
- an assessment of the geological and physiographical setting of both Fort Carson and PCMS;
- historic air photographs, potentially showing the age of gully systems; and
- measurements from further site investigations.

The additional site investigations themselves are expected to comprise:

- detailed surveys of cross-sections of at least one gully system;
- an assessment of the vegetation around the gullies;

- soil infiltration measurements; and potentially
- soil sampling of layers of the Little Grand Canyon, in an attempt to date the prehistoric erosional and accretionary stages and correlate them with estimated climatic conditions at the time.

More accurate and extensive data on the Fort Carson and PCMS sites will allow more in depth simulations of gully evolution. In the process of running the simulations, it is expected the CHILD program will be modified to better cater for processes involved in gullying which may be currently lacking.

With a sounder understanding of gully behavior, the focus of the project will change to one of erosion rehabilitation and prevention. Currently, some qualitative knowledge exists pertaining to remedial measures, but to efficiently and effectively remove the threat of gullies, more quantitative predictions are crucial. Simulating gully erosion with particular remedial measures in place will shed light on their relative strengths and weaknesses, in terms of recovery time, cost, and stability.

Ultimately, this work will provide a framework for a decision support system to assist land managers in designing and simulating specific rehabilitation measures.

9.0 Broader Impact

The gully systems of Fort Carson and PCMS have many features in common with gullies and arroyos throughout the southwestern United States and in other semi-arid to arid settings. In particular, these similarities in morphology suggest that their origins and dynamics are similar to those of the arroyos of the south-west that have been the object of study throughout much of the 20th century. Widespread channel incision and arroyo formation throughout the southwestern U.S. toward the end of the 19th century had tremendous impacts on agriculture, as water tables were lowered and croplands destroyed; on road systems, as bridges and other engineering works were undermined; and on water quality and stream stability, as eroded sediment was transported downstream. Despite much attention to these problems, however, the dynamics of these incised channels remain poorly understood, and to date efforts to model them have been rudimentary. We believe that the current research effort, if continued beyond this proof-of-concept phase, will offer an opportunity to make a significant contribution to the classic "arroyo problem" by bringing to bear cutting-edge technology for landscape erosion and sedimentation modeling.

10.0 Interaction, Collaboration and Technology Transfer

The visit by the MIT team to Fort Carson in October, 1999, provided an opportunity for us to brief land managers on the capabilities of the CHILD model and research findings to date. In addition, a visit to USACERL was conducted in July, 1999, by R, Bras, G. Tucker, and N. Gasparini, also to brief land management and cultural resources personnel on the model and research findings. A copy of the CHILD model version 2.0, along with a full set of reports and documentation, was delivered to Dr. Zeider of USACERL (now at Colorado State University) in July, 1999, and installed on the CERL network. The reports reside in the USACERL library.

11.0 PI Professional Activities and Student Support

In December, 1999, G. Tucker co-hosted a session with G. Willgoose on "Testing Models of Drainage Basin Morphology" at the American Geophysical Union meeting in San Francisco. The project is supporting master's thesis work by D. Collins, and PhD research by N. Gasparini.

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